A Hard X-Ray Telescope for an X-Ray Spectroscopy Mission, Extending the Bandwidth

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Category of Response: **Instrument Concept**
Willing to participate and present concept: **YES**

Summary

In response to FRI NNH11ZDA018L, which solicits concepts for the Next NASA X-ray Astronomy Mission we are proposing a hard X-ray telescope (HXT) that extends the bandwidth to ~70 keV and complements the soft X-ray high resolution soft X-ray spectrometers that other teams are proposing. The HXT would be an independent modular instrument, containing both telescopes and detectors. Its estimated cost and mass would be only very small increments upon the mass and cost of the principal spectroscopy payload. The HXT¿s optic axis is aligned within a few arc minutes with the spectroscopy telescope and observes in parallel with it. It would satisfy two of the NWNH science objectives identified in Table 1 of the RFI. The effective area would be about 250 cm^2 at 30 keV, which exceeds the "Key IXO performance requirement" of 150 cm^2 effective area at 30 keV. In comparison to other types of hard X-ray telescopes our belief, which is based on our laboratory measurements and the performance of electroformed telescopes in orbit is that our technology will have equal or more effective area and better angular resolution and therefore the most sensitivity.

Properties of the Hard X-Ray Telescope Package

Number of Telescopes/Detectors*	2
Type of Telescope	Electroformed Integral Wolter 1 mirror shells
Diameter (each of 2 telescopes)	34 cm
Focal Length*	10 m
Effective Area at 30 keV	250 cm^2
Expected Angular Resolution	22 arc sec HPD
Field of View	12 arc min FWHM
Mass	98.4 kg
Power	15 w Not including thermal control of telescopes
TRLs	Optics:6 Detector:8
Cost (2011$)	24.15 M

*Number of telescopes depends upon focal length. For example if the focal length were reduced to 7 m there would be 3 smaller diameter telescopes and 3 detectors to maintain the same area.

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1. Introduction

We are responding to the Request for Information (RFI) concerning the development of a new X-ray astronomy mission to replace the International X-Ray Observatory (IXO). This paper does not describe a complete X-ray spectroscopy mission. We advocate including a hard X-ray telescope (HXT) that will observe in the 10 to 70 keV band simultaneously with the soft X-ray spectrometers. One objective is to measure a component of the spectrum that probably has a non-thermal origin and is perhaps more intimately connected to the underlying energy source of all the electromagnetic radiation than the lower energy X-ray lines. The spectral energy density of the X-ray/hard X-ray spectrum of an AGN generally peaks in the 30 to 50 keV band. Therefore, it is appropriate for spectroscopic measurements to include this regime. In addition the 20 to 70 keV band may contain interesting features associated with cyclotron radiation as observed in Her X-1 (Voges et al, 1982). Some models predict that cyclotron features will occur above 10 keV in the spectrum of neutron star binaries (Dipanjan and Dipankar, 2011). Another objective is to obtain an accurate measurement of the continuum spectrum of a source in order to measure the profile of a low energy X-ray line that has been broadened as a result of traversing a region of strong gravity or has been scattered. The Fe Kα line emitted by an AGN is of particular interest. The extended bandwidth of the HXT will make it possible to measure the magnitude and functional form of the continuum to determine the intrinsic profile of the broadened line with less ambiguity. X-ray sources including SMBH's are notoriously variable. The hard X-ray continuum spectrum measured at another time may not the same when the object is observed by the high resolution X-ray spectrometers.

We describe an HXT and its expected performance based upon work and measurements that were accomplished with support to SAO and MSFC from NASA's Constellation-X, IXO, APRA and balloon programs.

2. Hard X-Ray Telescope

Table 1 of the RFI: "Primary IXO Science Objectives" specifically states that an instrument with 150 cm^2 effective area at 30 keV is needed to address the first two science questions. To satisfy this requirement we are advocating that the new mission include an autonomous hard X-ray telescope package that observes simultaneously with the soft X-ray spectrometers. This document contains a description of an HXT package with estimates of its performance, mass and approximate cost. We believe that the mass and cost of the HXT package are rather modest and can be accommodated without a significant effect upon the mass, cost, and schedule of the integrated X-ray spectroscopy mission. The HXT package places no constraints upon the soft X-ray spectrometers other than it leave sufficient spacecraft resources to accommodate it.

The broad bandwidth of the HXT is achieved by the use of multilayer coatings upon telescopes with low graze angles. As an alternative to an autonomous HXT we considered depositing multilayer coatings on the low energy X-ray telescopes. We rejected this option. Multilayer coatings would reduce the effective area of the low energy spectrometer because their reflectivity of multilayer coatings below 10 keV is inferior to that of a single layer of iridium or platinum. In addition multilayer coatings would introduce more complexity in the effective area as a function of energy. The consequence would be more difficulty in the interpretation of spectra. An even more compelling reason for rejecting this option is that the optimum microcalorimeter for the focal plane of the spectroscopy telescope would not be efficient in the 20 to 70 keV band. It may be possible to increase the hard X-ray efficiency of the microcalorimeter by using materials with more stopping power. However, that is likely to degrade the energy resolution at 0.15 to 8 keV, the prime energy band of the spectroscopy mission.

The bandwidth of the low energy spectrometers may not be sufficiently broad to accomplish one of the most important scientific objectives of a spectroscopy mission: It is obtaining unambiguous measurements of the profile of $K\alpha + K\beta$ fluorescence lines of iron that has been redshifted into a broadly extended feature by the strong gravity fields that exist in the vicinity of an accreting black hole. The extended bandwidth of the HXT will make it possible to measure the magnitude and functional form of the continuum that is superimposed upon the Fe feature with much greater confidence.

3. Observing a gravitationally broadened Fe line

Observing and quantifying the gravitational redshift in the vicinity of black holes will provide new information about the behavior of matter in strong gravitational fields and the laws of general relativity. The nearby ($z = 0.00775$) Seyfert galaxy MCG-6-30-15 contains a prime example of a gravitationally-broadened Fe line. The abundance of iron is 2 to 3 times solar (Fabian et al, 2002). The broad-line effect was discovered by ASCA (Tanaka et al, 1995) and has been observed since by ASCA again on several occasions, as well as by BeppoSAX (Guainazzi et al, 1999), and RXTE (Lee et al, 1999, Vaughan and Edelson, 2001). Furthermore, there was a long XMM-Newton exposure (Wilms et al, 2001) and a more recent Suzaku observation (Miniutti et al, 2006). Brenneman and Reynolds, 2006, consider several models including the spin of the black hole that could explain the shape of the broad Fe line.

A figure in the Suzaku paper illustrates why it is desirable to have good data at 20 keV and above for interpreting the spectrum. Fig. 1 is the energy spectrum of MCG-6-30-15 relative to a function that varies as E^{-2}. The points at energies up to 12 keV (black) are data from the CCD detectors (XIS) and the higher energy points (red), which extend to about 40 keV were obtained by a combination of a PIN diode and a GSO crystal scintillator. Between the Compton hump

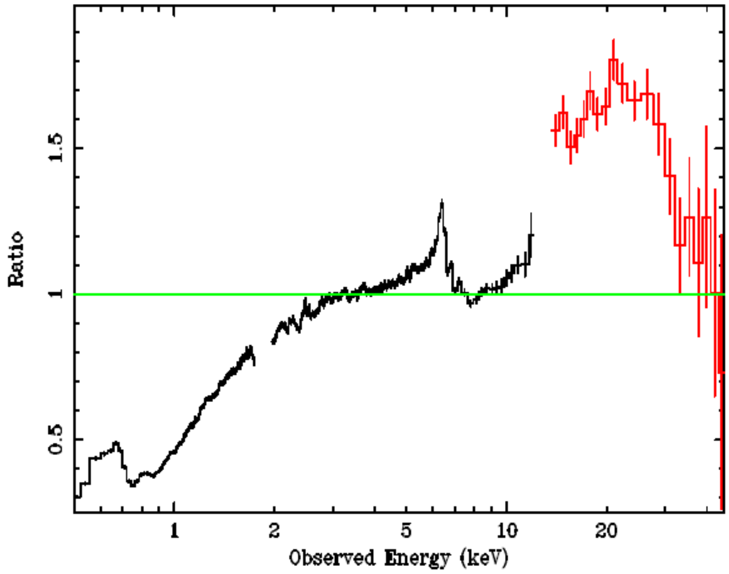

Figure 1: Energy spectrum relative to the function E^{-2} of the Seyfert galaxy MCG-6-30-15 as seen by Suzaku. This figure is a reproduction of Fig. 4 of the paper by Minuitti et al, 2006.

whose effects appear to extend down to the region of the Fe line, the broadened Fe line, and the absorption at low energy, the energy range where the ratio of the observed spectrum to a power law continuum is constant is very small. Consequently there is considerable ambiguity concerning the shape of the continuum and of the broadened Fe line..

Fig. 2 is reconstructed from the Suzaku data shown in **Fig. 1**. The Suzaku data points (red circles) are the ratios with respect to a continuum function that varies as E^{-2}. Two other sets of data points are shown: in one the amplitude of the E^{-2} reference function is changed by 2% (blue crosses) and in the other the exponent of the power law reference function is changed by 5% to to $E^{-2.1}$ (black squares). Differences among the three sets of points illustrate the ambiguity of determining the precise shape of the gravitationally-broadened Fe line and how dependent that is upon the knowledge of the continuum. **Fig. 1** suggests that the influence of the Compton hump persists down to 7 keV and perhaps even lower. The X-ray spectroscopy mission will certainly observe many other objects with the goal of studying the gravitationally-broadened Fe line. These observations may include cases where the Compton hump has even greater influence upon the continuum in the region of the red shifted Fe line.

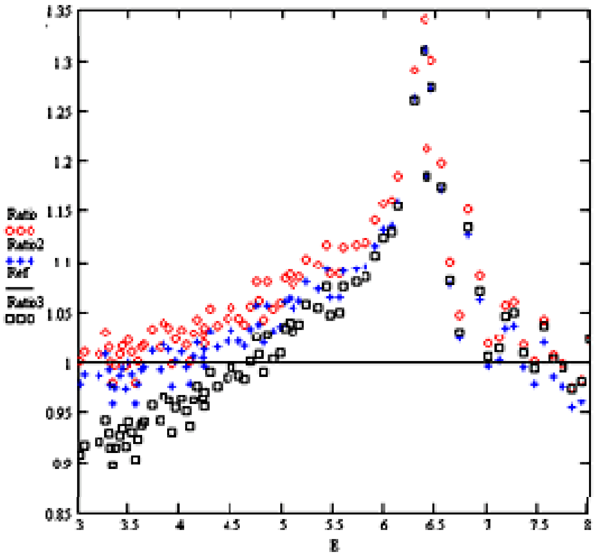

Figure 2: Suzaku data points that appear in Fig. 2 of Minuitti et al, 2006 are reproduced here without the error bars (red circles). Two other sets of data points are shown, blue crosses and black squares, based upon slightly different underlying continuum spectra.

A paper by Nandra et al, 2006, contains a figure, which is reproduced below in part (**Fig 3**.), that shows the presence of broadened Fe lines in eight Seyfert galaxies observed by XMM-Newton. In each case the data have larger errors than the MGC-6-30-15 data but one can see that the Fe line profile varies considerably from one object to another. This is not surprising given that the black holes at the center of each Seyfert do not all have the same mass and spin.

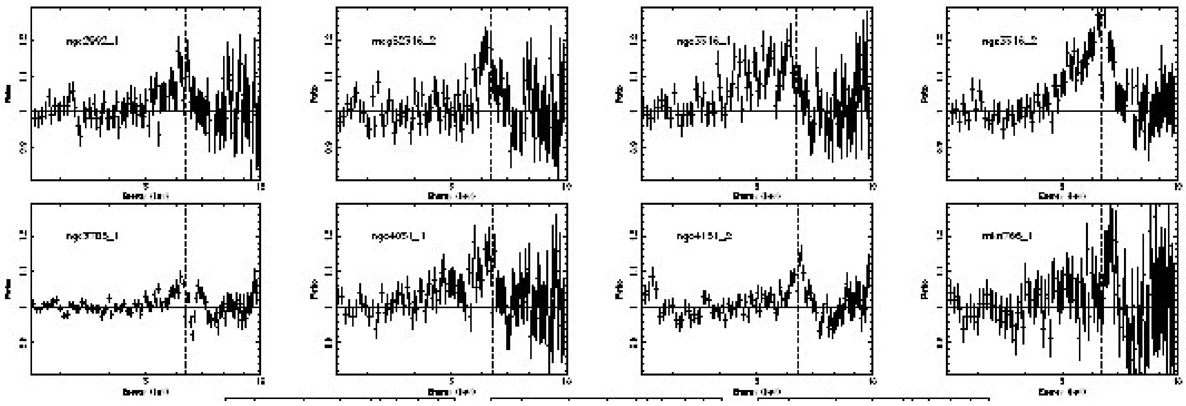

Figure 3: Spectra of eight Seyfert galaxies relative to a power law reference as observed by XMM-Newton (taken from a figure that appears in Nandra et al, 2006).

Evidence for a gravitationally-redshifted and broadened Fe is supported by observations of ASCA, Suzaku, and XMM-Newton. However, in all cases the error bars are large and one can have doubts that the contribution of the continuum to the spectrum below 6.4 keV has been taken into account accurately. The high resolution spectrometers of the new spectroscopy mission will reduce the error bars significantly and measure the energy profile of the redshifted Fe line plus continuum with much greater precision. Thanks to the high spectral resolution of the detectors it will also be possible to detect absorption edges and absorption lines. However, in order to subtract the continuum and isolate the Fe line profile unambiguously it will be necessary to observe the continuum and Compton hump simultaneously over an energy band that extends well beyond the high energy cutoff of the low energy spectrometers.

4. Technical Description

4.1 Overview

Up to this point our discussion has been independent of the details of the HXT other than that it should be a separate focusing telescope with multilayer coatings and have its own detector system. Two focusing hard X-ray telescope systems are scheduled to be in space within the next few years. They are NuSTAR and the hard X-ray telescopes of Astro-H. Copies of either of those instruments would extend the bandwidth of the X-ray spectroscopy mission. However, we would propose an HXT based upon another technology, electroforming integral parabolic + hyperbolic cylinders of revolution. The X-ray telescopes in space that were made by this process have much better angular resolution than NuSTAR and Astro-H. Essentially all hard X-ray measurements will be background limited. With a fixed collecting area a factor of ***F*** improvement in angular resolution results in a factor of ***F*** improvement in sensitivity. The three XMM-Newton telescopes and the Swift XRT were electroformed. All the telescopes of the Russian SRG mission are being made by electroforming. MPE will provide the seven eROSITA telescopes and IKI (the Russian Space Research Institute) in collaboration with the Marshall Space Flight Center is providing the higher energy ART-XC telescopes.

The technology we propose for the HXT is based upon electroforming nickel/cobalt integral replicas and depositing multilayer coatings on their interior surfaces.

MSFC has developed a process for producing integral mirror shells up to a factor of ~four times thinner than the thinnest shells used on XMM. SAO has developed a TiN hard coat for the mandrel that allows the replicas to separate easily and the mandrel to be re-used for multiple rounds of electroforming replication with no (or very little) re-polishing required.

4.2 Hard X-ray Test of electroformed mirrors with multilayer coatings

100-micron thick replicas with diameters 15 and 23 cm were electroformed. The 23 cm shell was coated at SAO with a broad band W/Si multilayer whose period varied with depth. The two mirror shells were integrated into a structure. The telescope assembly is shown in Fig. 4. X-ray tests of the system were carried out at the Panter facility in Germany in collaboration with the Brera Observatory (Romaine et al, 2007 and Romaine et al, 2009). The focal plane detectors were a ROSAT-like PSPC for low energies and an pn-CCD for the higher energy measurements.

Figure 4: Telescope assembly containing two mirror shells. The angular resolution was tested at the Panter facility. The Brera Observatory and the Panter staff collaborated in the measurements.

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Results of the X-ray tests are shown in Fig. 5.

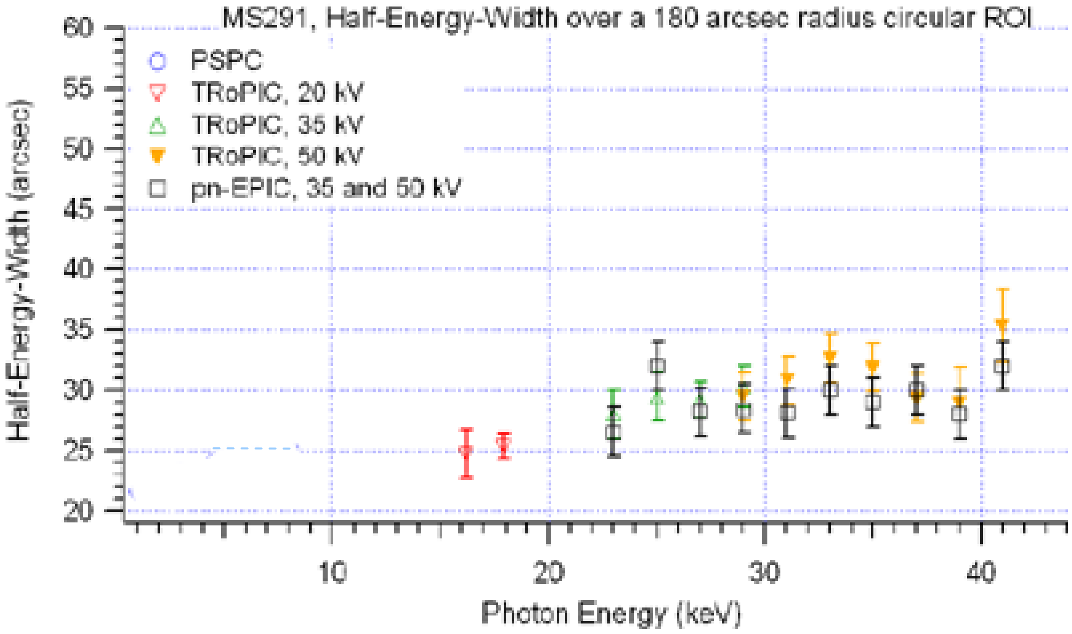

Figure 5: The angular resolution (half power diameter) of the telescope shown in Fig. 4 as measured in X-rays at the Panter facility.

The angular resolution at 40 keV is about 30 arc seconds. After the measurements were made we developed a new method of integrating the mirror shells into the structure that results in a more accurate alignment of their focus. With this new procedure we believe the resolution can be improved to about 20 arc seconds.

5. Sample configuration of a hard X-ray telescope system

For the purpose of estimating the mass and cost of a hard X-ray telescope system we consider a two module package. The focal length is assumed to be 10 m but can be varied as necessary to be compatible with the spacecraft. Each telescope contains 68 nested mirror shells ranging in diameter from 15 cm to 34 cm. Each mirror is a 60 cm long monolithic structure containing both the parabolic and hyperbolic sections. The shells are fabricated from a high-strength nickel-cobalt alloy. They are 100 micron thick out to 25 cm diameter and gradually increase in thickness to 150 microns at 34 cm. A composite housing, matched to the thermal expansion coefficient of the nickel alloy contains the shells which are held in place by a pair of diamond turned spiders, fabricated in steel.

For any type of focusing hard X-ray telescope the focal plane detectors are likely to be similar to those developed for the HEFT and NuSTAR programs. These are pixellated cadmium-zinc-telluride devices with custom readout chips and have high quantum efficiency and excellent energy resolution , < 1 keV FWHM) over the bandwidth of interest. A 500-micron-resolution detector oversamples the point source image from a 10-m-focal length, 20 arcsec HPD optic by a factor of two. We can expect smaller pixel detectors to be available in the future. Total detector power (2 units) is expected to be around 15 W, including detector heaters, but excluding mirror thermal control.

Estimated Total Mass for 2 HXT modules

Item	**Mass (kg)**
Shells	29.6
Housings + blanket	6.75
Detectors + electronics	13.0
Sub-total per telescope	49.4
Total	**98.4**

6. Estimated Costs

Telescope cost estimates are based on significant optics fabrication experience at MSFC. Some twenty mandrels, ranging in size from 5 cm to 50 cm in diameter have already been fabricated in house and over 150 shells have been replicated from these. Similarly, costs for assembly, testing and calibration are based on significant in-house experience. Costs for the focal plane detectors are based on previous experience with Con-X and studies carried performed for the NuSTAR program. Costs are solely for fabricating, testing, calibrating, delivering and integrating the HXTs.

Estimated Cost for 2 Hard X-Ray Telescopes (FY 2011 Dollars)

Item	**Cost ($)**
Mandrels	6,250,000
Shells + coatings	2,750,000
Housings	140,000
Assembly	65,000
Testing	55,000
Detectors + electronics	9,000,000
Calibration	100,000
Integration	220,000
Contingency (30%)	5,570,000
Total	**24,150,000**

7. Expected Performance

Figure 6, below, shows the total system effective area as a function of energy for the two-telescope configuration.

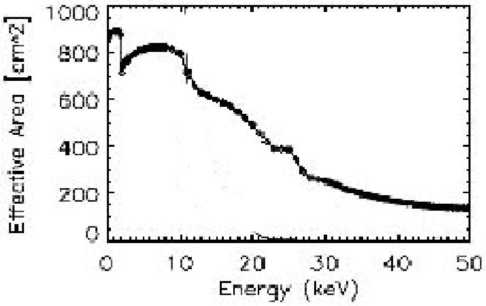

Figure. 6: Effective area of the proposed 2-telescope HXT as a function of energy.

We have calculated the expected (5-sigma) continuum sensitivity for the HXT configuration with this total effective area. **Figure 7** shows the sensitivity as a function of energy for two integration times, 10^5 sec and 10^6 sec. The background for this calculation was taken from Armstrong et al, 2000, who performed a detailed simulation of an HXT reference configuration in an L2 orbit. Note that most of the detector weight in the above table is in the BGO/CsI anticoincidence shields. Lighter shields could be investigated (such as plastic scintillators plus a modest amount of passive shielding); the small focal spot of the 22 arcsec optics helps in this regard as a factor of two increase in background at 20 keV only degrades the 10^5 sec sensitivity by 10%.

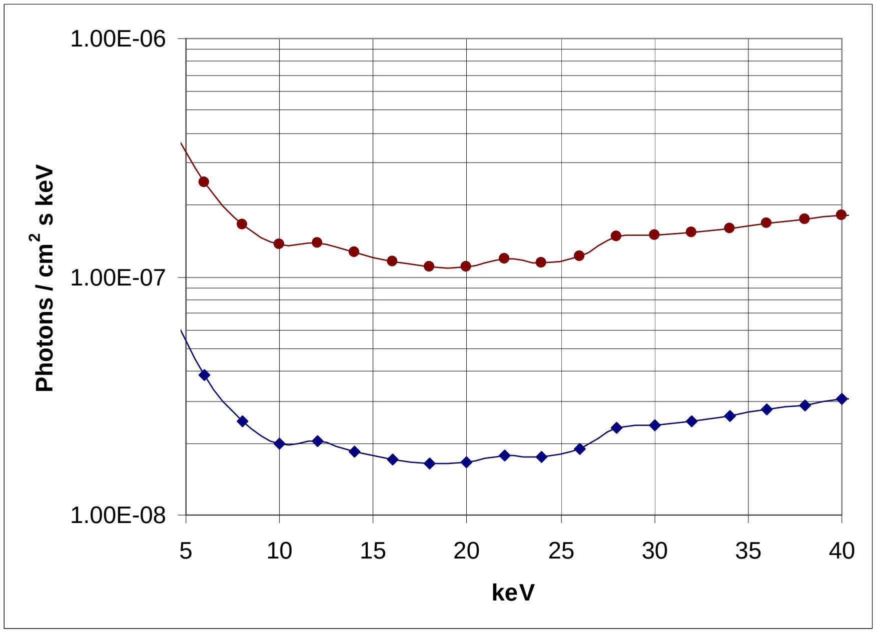

Figure. 7: Continuum sensitivity of the proposed 2-telescope HXT configuration. Shown are (5-sigma) curves for 10^5 and 10^6 sec

The above data show that a considerable increase in collecting area above 15 keV can be obtained for a modest outlay in resources. Note that we have presented just one multilayer configuration, and that there is flexibility for enhancing higher energy regions as necessary at a slight expense for lower energies. Note also that the effective area scales with mass. With a more generous mass allowance extra mirror shells could be added to each telescope and/or the number of telescopes could be increased.

8. Technical Readiness

The technology for the proposed HXT system is already well advanced. For example, we have already fabricated shells of the appropriate diameter and thickness for the proposed telescope and have demonstrated angular resolution at the 30 arcsec level. We firmly believe that this can be further improved on with a new alignment and mounting scheme and have a goal of 20 arcsec HPD per telescope. We currently have 112 shells in 8 mirror modules flying on the HERO balloon payload, and of course the electroformed nickel replication technology has been used extensively on previous satellite missions. Considerable flight heritage exists with XMM-Newton and the Swift XRT. The Russian SRG spacecraft will provide even more experience. SRG will have two electroformed telescope systems, eROSITA and ART-XC. In addition to our tests the performance of multilayer coatings has been verified by NuSTAR and Astro-H ground tests. The TRL level of the optics system is 6.

Appropriate CdZnTe focal plane detectors have been successfully flown on the HEFT balloon payload, and have passed all tests of the NuSTAR detectors. The NuSTAR detectors can be adopted as is although a factor of two finer size pixel would be advantageous. The TRL level of the detectors is estimated to be 8, actual system completed and "mission qualified" through test and demonstration in an operational environment (ground or space).

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